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# A postmortem investigation of the Type IIb supernova 2001ig

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## ABSTRACT

We present images taken with the GMOS instrument on Gemini-South, in excellent (<0.5 arcsec) seeing, of SN 2001ig in NGC 7424, ∼1000 days after explosion. A point source seen at the site of the SN is shown to have colours inconsistent with being an H II region or a SN 1993J-like remnant, but can be matched to a late-B through late-F supergiant with $A_V < 1$. We believe this object is the massive binary companion responsible for periodic modulation in mass loss material around the Wolf-Rayet progenitor which gave rise to significant structure in the SN radio light curve.

**Key words:** stars: evolution – supernovae: general – supernovae: individual: SN 2001ig – binaries – galaxies: individual: NGC 7424.

## 1 INTRODUCTION

Supernovae (SNe) of Type II, Ib, and Ic are all now recognised as arising from the core collapse of a massive ($> 8$ M$_\odot$) star, but with progressively less H and He in their outer layers. As a result, early spectra from Types Ib and Ic lack any H features, while Type Ic even lack any He features (Filippenko 1997). The rare class of Type IIb supernovae undergo a spectral transition from Type II to Type Ib as their hydrogen recombination lines fade. As such, they could offer important clues about the nature of this mass loss, via stellar winds or mass transfer in binary systems.

Two of the nearest examples of Type IIb SNe have also been found to be luminous at radio and X-ray wavelengths, indicative of interaction with a dense, pre-existing circumstellar medium (CSM): SN 1993J in M81 (Van Dyk et al. 2005; Zimmermann 2005), and SN 2001ig in NGC 7424 (Ryder et al. 2004, hereafter Paper I; Schlegel & Ryder 2002). The multi-frequency radio light curves of SN 2001ig showed clear modulations with a period $\sim 150$ days, due to corresponding changes in the CSM density. While thermal pulsations in the core of a single AGB star progenitor could in principle generate mass-loss shells with the appropriate spacing, Paper I argued instead that a massive binary companion in an eccentric orbit about a Wolf-Rayet (WR) progenitor would yield the necessary mass-loss enhancements near periastron. The 'pinwheel' dust nebulae formed from the colliding stellar winds have even been imaged directly in some Galactic WR binary systems (Tuthill et al. 2003).

The idea that mass-transfer in binary systems could induce the stripping necessary to account for the Type IIb phenomenon received a boost with the unmasking of a hot massive binary companion to SN 1993J, initially via photometry of pre-supernova imaging (Aldering et al. 1994) and ultimately via its signature in late-time ultraviolet spectra (Maund et al. 2004). We predicted (Paper I) that if the progenitor of SN 2001ig had a binary companion, then it too should become apparent, once the optical remnant had faded. In this Letter we report the results of multi-colour ground-based optical imaging, under excellent seeing conditions, which appear to show just such an object.

## 2 OBSERVATIONS AND DATA REDUCTION

Imaging of NGC 7424, which takes in the location of SN 2001ig, was conducted in queue mode with the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) attached to the Gemini-South Telescope for programme GS-2004B-Q-6 (PI: S. Ryder). Each GMOS image yields an unvignetted field of view ∼5.5 arcmin on a side, at 0.073 arcsec pix$^{-1}$. Observing was carried out on the night of 2004 Sep 13 UT when the seeing was 0.6–0.8 arcsec and conditions were photometric, and repeated on 2004 Sep 14 UT when the seeing was 0.35–0.45 arcsec but cirrus and thin cloud were present. On the second night a series of $5 \times 540$ s exposures in the Sloan Digital Sky Survey (SDSS) $u'$ filter, $3 \times 240$ s in $g'$, and $4 \times 530$ s in $r'$ were obtained, with each exposure offset by at least 5 arcsec spatially to allow filling-in of the inter-CCD gaps in GMOS. Images of the photometric

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standard field T Phe (Landolt 1992) were obtained as part of the baseline calibration for the first night.

The data were reduced and combined using V1.8.1 of the GEMINI package within IRAF[1]. A master bias frame (constructed by averaging with 3-$\sigma$ clipping a series of bias frames) was subtracted from all raw images in lieu of overscan fitting and subtraction. Images of the twilight sky in each filter were used to flatfield the images and suppress a prominent 'brick wall' pattern, particularly in $u'$. The dithered galaxy images in each filter were then registered and averaged together with the IMCOADD task to eliminate the inter-CCD gaps, bad pixels, and cosmic rays.

In order to precisely locate SN 2001ig in our GMOS images, observations of SN 2001ig taken 6 months after outburst were extracted from the ESO Science Archive. SN 2001ig was imaged with the FOcal Reducer/low dispersion Spectrograph (FORS2) on the Very Large Telescope UT4 during the night of 2002 June 16 UT as part of programme 69.D-0453(B) (PI: E. Cappellaro). Exposures of 90 s in $B$, 60 s in $V$, and 15 s in $R$ with a pixel scale of 0.252 arcsec pix$^{-1}$ were processed using IRAF in a similar manner to the GMOS data[2].

A section covering some 36 arcsec × 23 arcsec surrounding SN 2001ig was extracted from the final GMOS images in each filter, and a matching section extracted from the FORS2 images. These image sections were then all aligned to a common coordinate system and image scale using the GEOMAP and GEOTRAN tasks within IRAF by fitting to 15 stars in common. Figure 1 shows the FORS2 $B$, and GMOS $u'$, $g'$, $r'$ images of the neighbourhood of SN 2001ig. Though the SN appears saturated in all the FORS2 images, profile-fitting yielded a centroid position consistent to 0.3 resampled pixels which, including the r.m.s. of the GEOMAP fitting, results in an overall positional uncertainty of 0.03 arcsec in each axis. As Fig. 1 indicates, the position of the SN on the FORS2 image is coincident with a faint, point-like source in both the $g'$ and $r'$ images, but there is no counterpart in the $u'$ image. Rings and arcs of diffuse nebulosity are much more apparent in the $u'$ image, and the SN position falls on the northern rim of one such arc. If there is an ultraviolet counterpart to the source seen in the $g'$ and $r'$ bands, then it is unfortunately hidden within this emission.

## 3 PHOTOMETRY

Aperture photometry of the T Phe observations on 2004 Sep 13 was carried out using the PHOT task within IRAF, an aperture radius of 2.6 arcsec (35 pix), and sky level from the mode of pixels at radii between 2.9–3.7 arcsec (40–50 pix). While only stars A, C, and D from Landolt (1992) were within the GMOS field, Smith et al. (2005) have determined magnitudes in the SDSS system for these and three other stars in the same field, which have enabled us to derive independently the extinction, zero-points, and colour terms in $u'$, $g'$, and $r'$. We note this is the first time such quantities have been determined for GMOS on Gemini-South utilising calibrated SDSS photometry, rather than relying upon theoretical (Fukugita et al. 1996) or empirical (Smith et al. 2002; Karaali et al. 2005) transforms from the Johnson colours. For the T Phe observations, we find:

$$u' = (25.14 \pm 0.04) - 2.5\log(C/t) - 0.34X + 0.15(u' - g')$$

$$g' = (28.54 \pm 0.01) - 2.5\log(C/t) - 0.12X + 0.05(g' - r')$$

$$r' = (28.53 \pm 0.03) - 2.5\log(C/t) - 0.11X + 0.05(g' - r')$$

where $C$ = integrated counts within 2.6 arcsec aperture radius, $t$ is the exposure time, and $X$ is the airmass.

Using these relations, we have been able to 'bootstrap' a calibration for the Sep 14 data from the Sep 13 data, by determining mean offsets in each filter between the 2 nights for large-aperture measurements of 10 isolated field stars in each image. Due to the semi-crowded nature of the field shown in Fig. 1, measurements of these same 10 stars in apertures ranging from 0.4 arcsec out to 2.6 arcsec have also been obtained, allowing an empirical aperture correction to be applied in each filter when contamination by neighbouring stars in the large aperture might be a problem.

The magnitudes and colours for 30 stars in the neighbourhood of SN 2001ig (as identified in Fig. 1) are presented in Table 1. A few of these stars had no clear counterpart in the $u'$ image for PHOT to centroid on, so a 3$\sigma$ upper limit of $u' > 26.1$ has been adopted following the approach of Maund & Smartt (2005). The one exception to this is for the site of SN 2001ig itself, which sits within a region of diffuse nebulosity, and an aperture-corrected upper limit on the measured flux within a 0.4 arcsec aperture is $u' > 24.9$.

The colours of these 30 objects and the counterpart to SN 2001ig are plotted in Fig. 2. Also plotted in this diagram is the locus of unreddened colours for supergiant stars, transformed from the Johnson colours (Drilling & Landolt 2000; Lang 1991) to the SDSS system (Smith et al. 2002); the reddening vector equivalent to 1 mag of extinction in the $V$-band (Fan 1999); and an indicative error bar on each point which combines the uncertainties in the Sep 13 calibration, the bootstrapping to the Sep 14 data, the PHOT measurement, and any aperture correction.

As Fig. 2 indicates, stars in the neighbourhood of SN 2001ig are all consistent (to within the errors or colour limits) with being supergiants, or possibly young stellar clusters, suffering varying amounts of reddening. The reddest objects in $(g' - r')$ are so red that they are not detectable in $u'$. The extremely red colours of 4, 9, 16, and the background disk galaxy in Fig. 1 suggest the presence of a foreground dust lane running from just north, to the west of SN 2001ig. Star 17, just 3 arcsec south of SN 2001ig, is also absent in $u'$ but is intrinsically much redder than the SN. Where possible, we have 'de-reddened' each object back on to the supergiant locus in Fig. 2, and tabulated the estimated extinction and inferred spectral type in Table 1.

## 4 DISCUSSION AND CONCLUSIONS

### 4.1 Stellar companion or nebula?

De-reddening from the blue limit on $(u' - g')$ for SN 2001ig indicates an intrinsic spectral type for the companion of B7

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[2] A full-colour representation of these data can be seen at http://www.eso.org/outreach/press-rel/pr-2004/phot-33-04.html.

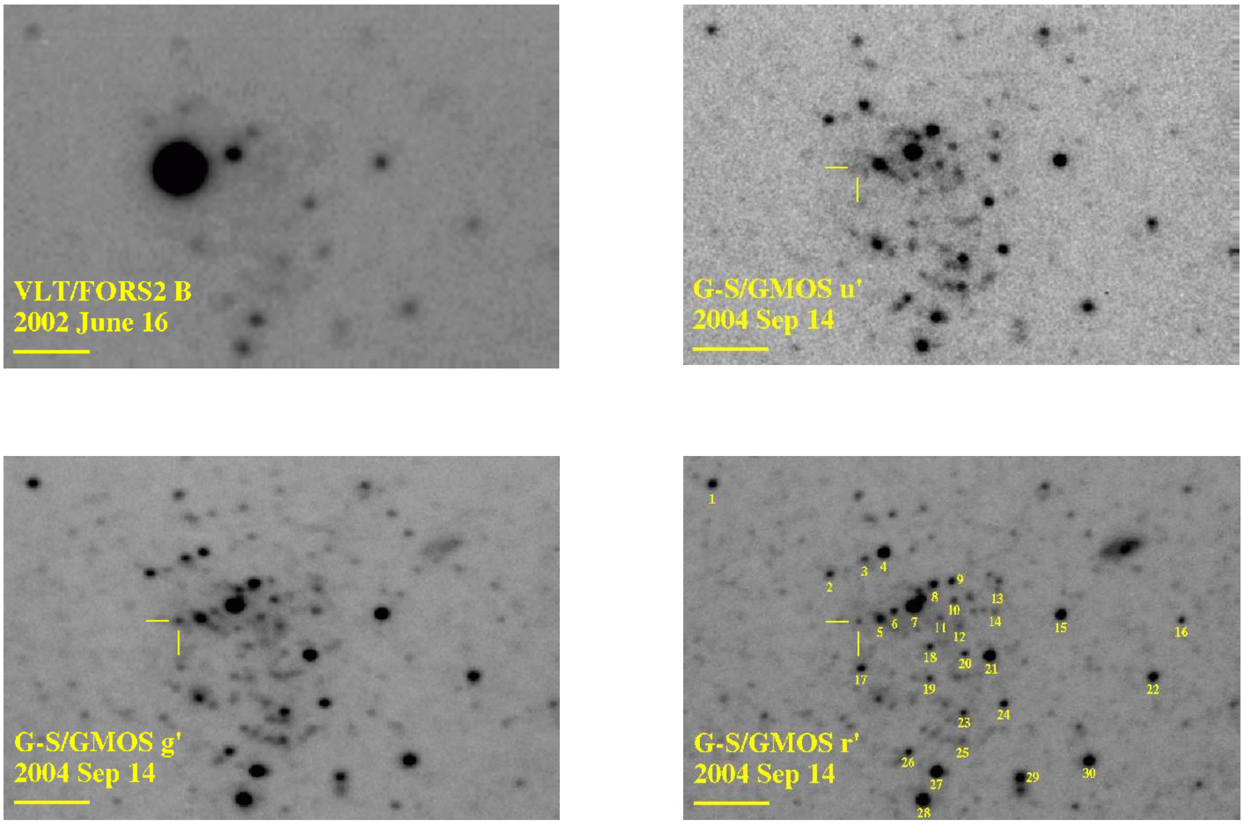


**Figure 1.** Images of the region immediately surrounding SN 2001ig in NGC 7424. North is to the top, with East to the left, and the line in the lower-left corner of each image is 5 arcsec in length. The two perpendicular lines in each of the GMOS images correspond to the centroid of the SN as measured from the FORS2 image. The numbers immediately below (or to the right of) stars in the $r'$ image identify the field stars for which colours have been measured in Table 1, and plotted in Fig. 2.

or later. However, the $(g' - r')$ colour and its uncertainty requires that it be no later than F8 with no reddening. In addition to the colours, we can use the absolute luminosity to attempt to constrain the spectral type, though this is subject to the usual distance uncertainties. For a distance of 11.5 Mpc (Tully 1988) and $A_V < 1$ then $M_{u'} > -7.0$, which requires a spectral type of B0 or later according to the stellar luminosity data and transforms used in Sect. 3. Similarly, $-6.2 > M_{g'} > -7.4$ constrains the type to be F8 or earlier, while $-6.3 > M_{r'} > -7.1$ implies a type between A1 and K8. Thus, both the colour and luminosity constraints are consistent in arguing for the presence of a late-B through late-F supergiant at the location of SN 2001ig.

While only the $u'$ image shows much nebulosity in this region, the effect of a foreground or background H II region needs to be considered. Aperture photometry of selected locations around a prominent 'bubble' nebula 40 arcsec east of the SN has been performed to determine the SDSS colour characteristics of a low-metallicity H II region. While their $(g'-r')$ colours are broadly similar to the SN, all were found to have $(u' - g') \lesssim 0$, much bluer than the SN or almost every other object in its vicinity. Those locations which included an ionising star/cluster have colours consistent with $A_V = 1 - 2$ mag O stars, while those which are purely nebulous have $(u' - g') \sim -1$, so are too blue to be stars.

Another potential contaminant could be the supernova remnant (SNR) itself. A decade after SN 1993J was discovered, its spectrum was still dominated by broad, box-shaped emission features (Maund et al. 2004). No spectra of SN 2001ig have yet been published, so we present in Fig. 3 a spectrum obtained on 2002 Sep 14 UT with the Anglo-Australian Telescope. A detailed spectral analysis is beyond the scope of this Letter, but we note that this spectrum bears strong similarities to spectra of SN 1993J at a similar epoch (day 286 in Matheson et al. 2000), with the notable absence of a broad H$\alpha$ component.

In order to assess the colour evolution of a Type IIb SNR in the SDSS system, we have performed synthetic photometry on the late-time spectra of Matheson et al. (2000), using the response curves of Smith et al. (2002). The zero-points were calibrated by matching the results on a flux-calibrated spectrum of the fundamental SDSS standard BD + 17°4708 (Bohlin & Gilliland 2004) to its defined values. The $(g' - r')$ colour of SN 1993J evolved from 1.0 at day 881, to 0.7 at day 976, and 0.6 by day 1766. It was not until day 2000 that it reached a colour similar to that observed in SN 2001ig, though dereddening by an amount corresponding to $A_V = 0.6$ mag (Matheson et al. 2000) would bring it just within range of the colour uncertainty on SN 2001ig by day 1766. Extended ultraviolet spectral cover-

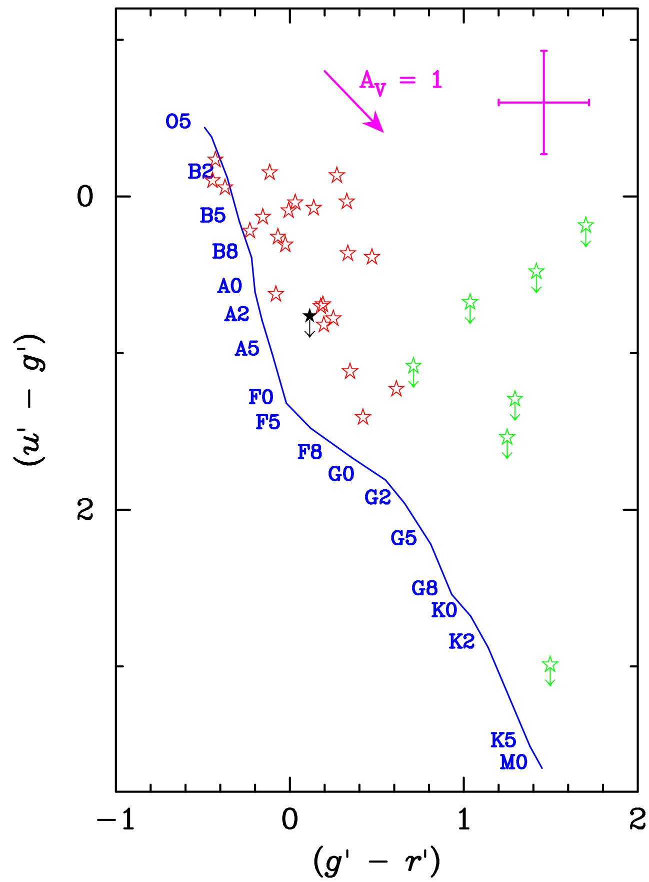


**Figure 2.** Two-colour diagram in the SDSS system for field stars labeled in Fig. 1 (open symbols) as well as SN 2001ig itself (filled symbol). Objects below the detection limit in $u'$ are shown with upper limits in $(u' - g')$. The locus of unreddened colours for supergiants stars is shown with their spectral type, as well as the reddening vector and indicative error bar [$\pm 0.33$ in $(u' - g')$, $\pm 0.26$ in $(g' - r')$].

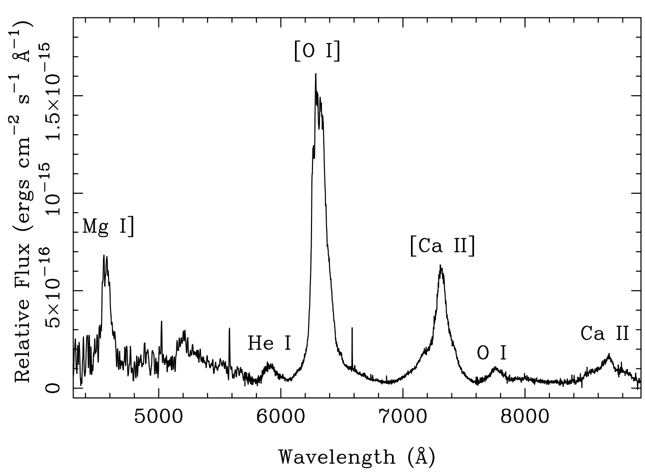


**Figure 3.** Composite spectrum of SN 2001ig obtained 285 days after explosion with the RGO Spectrograph on the AAT, combining a 3600 s exposure in the red and 600 s in the blue. The major emission lines are identified following Matheson et al. (2000).

**Table 1.** Photometry for objects in the neighbourhood of SN 2001ig.

| Star | $g'$ | $(u' - g')$ | $(g' - r')$ | $A_V$ | Sp. Type |
|---|---|---|---|---|---|
| 1 | 23.32 | 0.70 | 0.13 | 1.2 | B6 |
| 2 | 23.62 | 0.04 | 0.03 | 1.7 | <O5 |
| 3 | 23.51 | 0.26 | −0.07 | ∼3 | <O5 |
| 4 | 23.51 | > 2.99 | 1.50 | <3 | >G2 |
| 5 | 23.12 | −0.13 | 0.27 | 0.8 | B3 |
| 6 | 24.18 | 0.39 | 0.47 | ∼3 | <O5 |
| 7 | 21.54 | 0.08 | 0.14 | 1.5 | <O5 |
| 8 | 23.03 | −0.15 | −0.12 | 1.2 | <O5 |
| 9 | 24.98 | > 1.29 | 1.29 | <5 | <K4 |
| 10 | 23.84 | 0.63 | −0.08 | 0.4 | B9 |
| 11 | 24.12 | 0.03 | 0.33 | ∼3 | <O5 |
| 12 | 24.22 | 0.37 | 0.33 | 2.5 | <O5 |
| 13 | 24.39 | 0.09 | −0.01 | 1.9 | <O5 |
| 14 | 24.23 | −0.23 | −0.43 | ∼0 | B1 |
| 15 | 22.34 | 0.13 | −0.16 | 0.6 | B2 |
| 16 | 25.95 | > 0.19 | 1.70 | – | – |
| 17 | 24.77 | > 1.54 | 1.25 | <5 | <K4 |
| 18 | 25.01 | 0.68 | 1.04 | <4.5 | <K0 |
| 19 | 25.16 | > 1.08 | 0.71 | <3 | >B1,<G3 |
| 20 | 25.69 | > 0.48 | 1.42 | <5 | <K8 |
| 21 | 22.45 | 1.41 | 0.42 | 1.9 | A0 |
| 22 | 23.02 | 0.69 | 0.14 | 1.2 | B5 |
| 23 | 23.49 | −0.06 | −0.37 | ∼0 | B3 |
| 24 | 23.28 | 0.22 | −0.23 | 0.2 | B5 |
| 25 | 23.90 | −0.10 | −0.45 | ∼0 | B2 |
| 26 | 23.67 | 0.31 | −0.03 | 0.9 | B3 |
| 27 | 22.30 | 1.12 | 0.35 | 1.6 | B9 |
| 28 | 22.19 | 0.82 | 0.15 | 1.0 | B8 |
| 29 | 23.53 | 1.23 | 0.61 | 2.6 | B6 |
| 30 | 22.63 | 0.78 | 0.20 | 1.4 | B6 |
| SN | 24.14 | > 0.76 | 0.11 | <1.0 | >B7,<F8 |

age after day 2000 allows us to constrain $(u' - g') \lesssim 0.6$ at this epoch for SN 1993J, which is even bluer than the blue limit on SN 2001ig. Thus, even if SN 2001ig had evolved significantly faster than SN 1993J (though Fig. 3 gives us no reason to expect this), its SNR might never become blue enough in $(g' - r')$ [or red enough in $(u' - g')$] to fully account for the properties of the object we see at the location of SN 2001ig.

### 4.2 The progenitor systems of Type IIb supernovae

SN 2001ig is thus perhaps the second Type IIb event shown to have a massive binary companion to the progenitor. For SN 1993J, the progenitor is thought to have been a 5.4 $M_\odot$ K supergiant with $\log L/L_\odot = 4.5 - 5.5$, while the companion is now a 22 $M_\odot$ B2 Ia star of similar luminosity (Maund et al. 2004; Van Dyk et al. 2002). Both started out having initial mass $\sim$ 15 $M_\odot$, but mass transfer to the companion caused their evolutionary paths to diverge. In the case of SN 2001ig, no pre-explosion imaging of sufficient quality exists to constrain the progenitor spectral type, but as Paper I discusses, the radio light curve provides strong evidence for a WR progenitor, which typically has $\log L/L_\odot = 4.9 - 5.3$ (Lang 1991). In close binary systems involving a WR star and an OB companion, the mass of the WR star can range anywhere from 5 to >50 $M_\odot$

(Tutukov & Cherepashchuk 2003), with much of this variation due to the extent of mass transfer that has already occurred. The companion star to SN 2001ig appears to have $\log L/L_{\odot} \sim 4.5$, and $M = 10 - 18$ $M_{\odot}$ (Drilling & Landolt 2000) based on its SDSS colours and inferred spectral type.

Although both events appear to have occurred within massive binary systems, the optically-thin decline in radio flux was much smoother in SN 1993J than in SN 2001ig. Hydrodynamical modelling by Schwarz & Pringle (1996) indicated that the effects of varying CSM density on the radio flux become more pronounced as the viewing angle approaches the orbital plane. Although based on a small sample, this might explain why not all Type IIb/Ib/Ic radio light curves exhibit such pronounced structure, even if they all originated in WR + massive companion binaries. Soderberg et al. (2005) found an uncanny resemblance between the radio light curves of the Type Ibc SN 2003bg and those of SN 2001ig, even down to having almost identical intervals between bumps. They argue that this is too much of a coincidence to be explained by the binary viewing angle scenario, and propose instead that the progenitor systems of both SNe are single WR stars undergoing enhanced mass loss episodes every decade or so in the lead-up to the explosion. However, they can offer no physical explanation for the cause of this phenomenon or its periodicity, whereas the existence of a massive binary companion as revealed here for SN 2001ig provides a natural and simple means of modulating mass loss in the WR progenitor. Even where pre-explosion archival data is not available, ongoing postmortem investigations such as this one can still help us reconstruct the circumstances surrounding the death of massive stars and whether other parties were involved.

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